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# THE PHYSIOLOGICAL EFFECTS OF CURRENTS OF VERY HIGH FREQUENCY

## (135,000,000 TO 8,300,000 CYCLES PER SECOND)

BY

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# THE PHYSIOLOGICAL EFFECTS OF CURRENTS OF VERY HIGH FREQUENCY (135,000,000 TO 8,300,000 CYCLES PER SECOND)[a]

By J. W. SCHERESCHEWSKY, Surgeon, United States Public Health Service

This paper reports the results of studies of the effects upon small laboratory animals (mice) of electrical oscillations of very high frequency generated by a vacuum tube oscillator.

The modern development of the vacuum tube oscillator and associated circuits permits the generation of continuous wave currents of relatively pure wave form of very high frequency, sharply emitted at the frequency to which the circuit is tuned. This is not the case in the usual type of high frequency apparatus used for therapeutic purposes. Here, the oscillations are produced by condenser discharge across a spark gap. The oscillations produced in this way have a large decrement; the wave form is impure, giving rise to many harmonics; the emitted wave is broad, and consistent operation at the frequencies worked with in the studies here reported is difficult to obtain. Moreover, the oscillations generated are in the form of discontinuous trains separated by a period during which the upbuilding of energy for the next train occurs.

The physiological effects of high frequency currents generated by the vacuum tube oscillator appear to have been but little investigated. The only reference found by a search through the literature was a report by Gosset, Gutmann, Lakhovsky, and Magrou [1] on the effects of very high frequency radiation emitted by a vacuum tube oscillator upon plant tumors caused in the geranium by *Bacterium tumefaciens*.

The authors report that three geranium plants, bearing tumors caused by inoculation with the above-mentioned organism, were exposed to radiations emitted by a vacuum-tube oscillator at a frequency said to be about 150,000,000 cycles per second. One plant was given 2 exposures of three hours on consecutive days, one plant 3, and one plant 11 such exposures. After 16 days from the first exposure, the tumors, after growing in the interval, began suddenly to necrose. The necrotic process was said to be complete in about 15 days, so that the tumor could be detached by slight traction. In 16 control plants the tumors grew rapidly to enormous size and recurred after surgical excision. Details, however, as to the apparatus and method of exposure are lacking.

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[a] Reprint from the Public Health Reports, vol. 41, No. 37, Sept. 10, 1926, pp. 1939-1963.

[1] A. Gosset, A. Gutmann, G. Lakhovsky, and I. Magrou: Essai de Therapeutique du "Cancer Experimental" des Plantes. Comptes Rendus de la Société de Biologie, Vol. 91, 1924, pp. 626-628.



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In the studies here reported the first step was a study of oscillators which might generate oscillations of sufficiently high frequency and the development of suitable auxiliary circuits in which the effects of such currents on small laboratory animals (mice) might be investigated.

At this point it is desired to express grateful acknowledgment to Prof. George W. Pierce and E. L. Chaffee, of the Cruft High Tension Laboratory of Harvard University, for permitting the use of the facilities of the Cruft High Tension Laboratory in the preliminary work and for much helpful advice; also to Mr. M. L. Dow and Mr. F. H. Drake, of the same laboratory, for collaboration, valuable assistance, and advice in the working-out, construction, and setting-up of apparatus and in making preliminary runs and tests.

Further grateful acknowledgment is made to Prof. M. J. Rosenau, of the Department of Preventive Medicine and Hygiene of the Harvard Medical School, for the use of the facilities of his department in the subsequent work. It is also desired to thank the General Electric Co. for furnishing three special vacuum tubes of low internal capacity.

### Description of Apparatus

*Vacuum tube oscillator.*—After considerable preliminary work in testing the suitability of various types of oscillators, the following types of circuit were settled upon as satisfactory:

For the generation of the highest frequency currents employed, (i. e., from 200,000,000 cycles to 60,000,000 cycles per second) the type of oscillator described by Huxford [2] was found excellently adapted. In the design of circuits intended to oscillate at these high frequencies, the interelectrode capacity of the tube, negligible at low frequencies, becomes an important limiting factor on the frequency of the oscillations generated. In Huxford's circuit the capacity formed by the tube elements is in series with the variable tuning capacity. Because of well-known physical considerations, this has the effect of reducing the minimum capacity at which the oscillating circuit may be resonated, and thus permits the generation of frequencies higher than would be possible with a tube having a given interelectrode capacity, were this capacity in shunt with the tuning capacity as is the case, for instance, in the well-known Hartley circuit.

Two oscillators of the type described by Huxford were constructed, one having a range of from about 200,000,000 cycles to 85,000,000 cycles and the other with a range of 150,000,000 cycles to 60,000,000 cycles per second. Figure 1 shows the circuit network and the accompanying photographs show the appearance of the oscillators.

Reference to the diagram and photograph of oscillator No. 1 (Pl. I) shows that the tuning inductance consists essentially of two parallel

[2] Huxford, W. S.: Standing Waves on Parallel Wires. Physical Review, Corning, N. Y., 2nd Series, Vol. 25, 1925, pp. 686-695.

brass rods 24 centimeters long, 4.7 millimeters in diameter, and spaced 5 centimeters, supported at each end by vertical bakelite strips. At the vacuum tube end the upper rod is connected to the grid, while the lower is connected to the plate of the tube. This lower rod is revolubly mounted and serves as a support for the rotary plate of the tuning condenser which is mounted on the rod by means of a sleeve and set-screw, so that it may be moved and fixed at any point on the

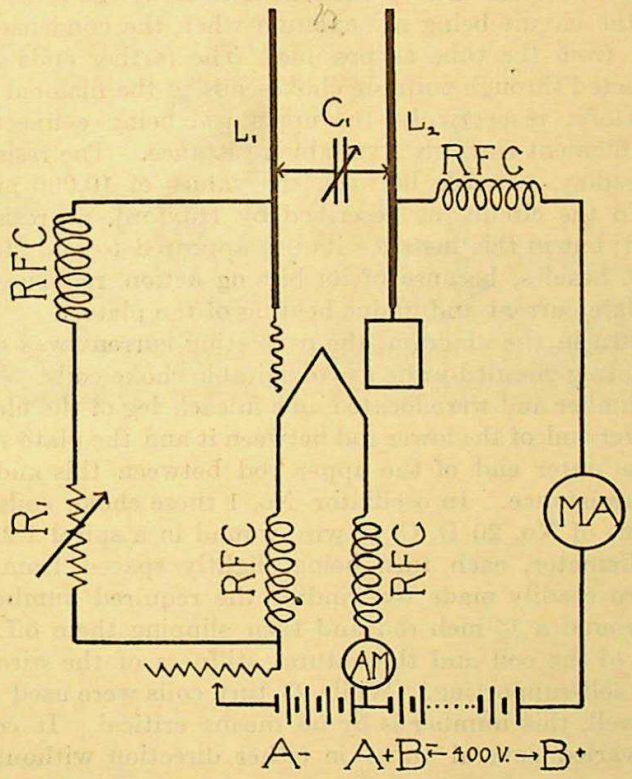



FIG. 1.—Circuit of oscillators Nos. 1 and 2 (Huxford circuit)
$L_1$, Grid inductance
$L_2$, Plate inductance
$C_1$, Tuning condenser
RFC, Radio-frequency choke-coils
MA, Plate millammeter
AM, Filament ammeter
R, Variable resistance (10,000–200,000 ohms)

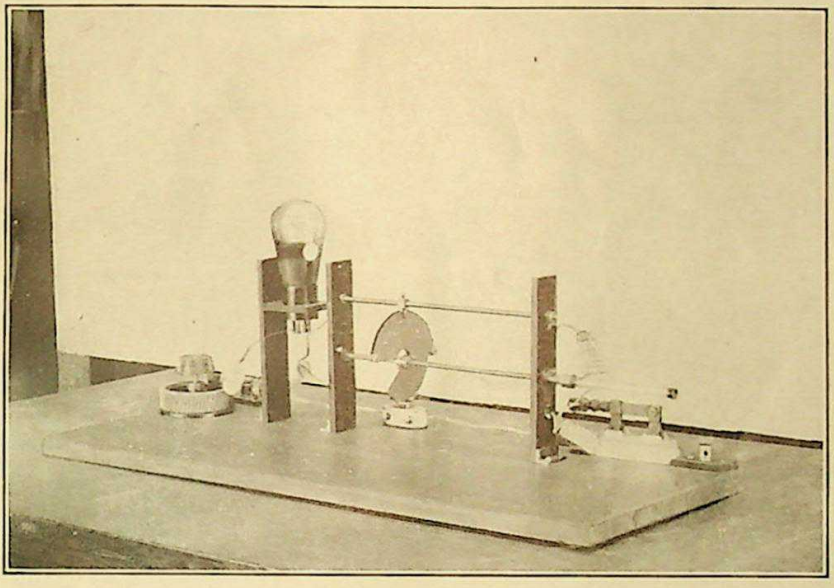
lower rod. The upper rod, which is not revoluble, carries the stator portion of the tuning condenser. This is suspended from a small brass block, bored to a sliding fit upon the upper rod and secured by a set-screw so that it may be appropriately located with respect to the rotary plate. The stator portion of the condenser consists of two plates spaced 3.1 millimeters from each other, with a radius of 4.7 centimeters. The rotary plate has a radius of 3.75 centimeters.

This arrangement of the tuning condenser which permits it to be slid to different sites along the rods is an important means of varying the oscillator frequency, as the range obtained by varying the condenser alone, at any one position on the rods is rather narrow. To get the benefit of the full range of frequencies of which the oscillator is capable, it is necessary to alter the value of the inductance in the oscillating circuit. This is done by sliding the rotor and stator portions of the condenser to different sites along the rods, the inductance in the circuit being a maximum when the condenser is slid as far away from the tube as possible. The farther ends of the rods are connected through suitable choke-coils to the filament and to the plate battery, respectively, the upper rod being connected to the negative filament through a variable resistance. The resistance used was a Bradley, variable between the values of 10,000 and 200,000 ohms. In the circuit, as described by Huxford, no resistance was employed; but in this instance its use appeared to add stability and efficiency, besides, because of its biasing action, reducing consumption of plate current and undue heating of the plate.

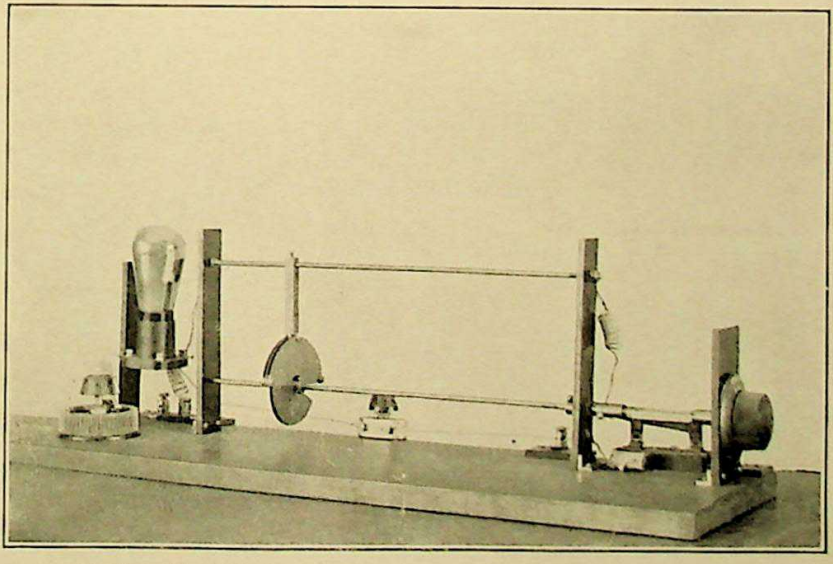
As shown in the diagram, the oscillating current was confined to the oscillating circuit by the use of suitable choke coils. These were four in number and were located, one in each leg of the filament, one at the outer end of the lower rod between it and the plate supply, and one at the outer end of the upper rod between this and the grid-biassing resistance. In oscillator No. 1 these choke coils consisted of 23 turns of No. 20 D. C. C. wire wound in a spiral 1.25 centimeters in diameter, each turn being slightly spaced from the next. They were readily made by winding the required number of turns tightly around a ½-inch rod and then slipping them off, the small diameter of the coil and the natural stiffness of the wire rendering the coils self-supporting. While 23 turn coils were used and found to work well, this number is by no means critical. It could probably be varied several turns in either direction without changing results.

Oscillator No. 2 was a duplicate, in constructional details, of the first oscillator, except for larger dimensions. The rods were 38 centimeters long and spaced 11.5 centimeters instead of 5 centimeters. The tuning condenser, too, was larger, having five instead of three plates. Because of the wider spacing of the rods, it was necessary to make the brass block which carried the stator of the condenser considerably longer than in the smaller model.

It will be noted, from the photograph, that, in the smaller oscillator, no socket for the tube was used, the tube being mounted by inserting the base, until stopped by the pin, in a hole of proper diameter, in a horizontally mounted bakelite strip. The plate, grid, and filament leads were then soldered directly to their respective tube prongs.



Oscillator No. 1 (Huxford circuit). Range 230,000,000 to 85,000,000 cycles



Oscillator No. 2 (Huxford circuit). Range 150,000,000 to 60,000,000 cycles

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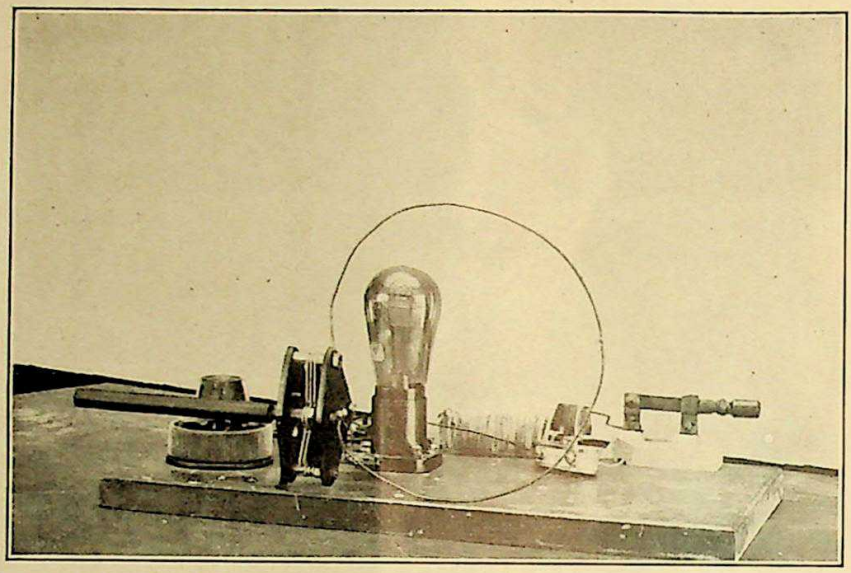
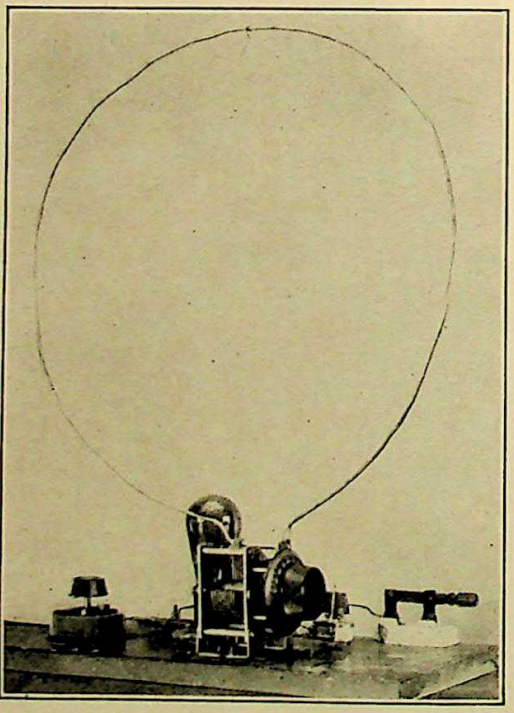
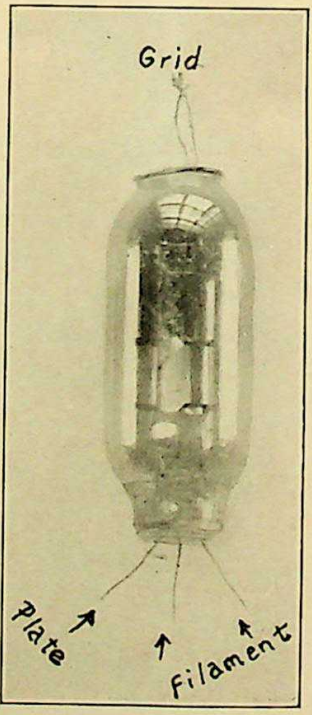


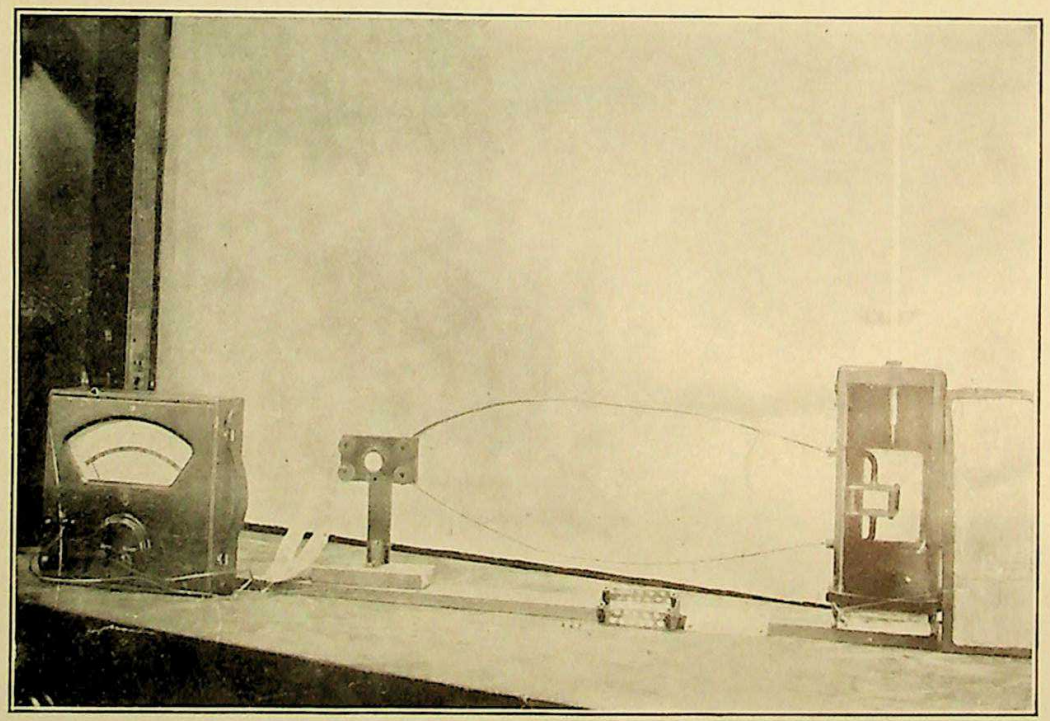
Oscillator No. 3 (Hartley circuit). Range 50,000,000 to 23,000,000 cycles



Oscillator No. 3 (Hartley circuit). Range 20,000,000 to 7,250,000 cycles




Special 5-watt vacuum tube with low internal capacity



Auxiliary-coupled circuit showing mouse holder, thermocouple, and microammeter

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This was done to avoid introducing unnecessary capacity in the circuit through the use of a socket. In the other oscillators, however, where lower frequencies were generated, this precaution was needless; consequently, for the sake of convenience, a socket was employed.

The vacuum tube used for the generation of high-frequency current was the UX 210. This tube has a thoriated filament, is rated at 7.5 watts, is used with a maximum filament current of 1.25 amperes at 7.5 volts. The plate potential employed was 400 volts, furnished by a suitable number of 6,000 m. a.-hour lead storage-cells.

This tube was found to oscillate vigorously in the circuit just described up to a frequency of 158,000,000 cycles. At this point the internal capacity of the tube and the inductance of its leads were so great that oscillations of higher frequency could not be obtained. However, by the use of the special tubes (shown in Plate II) having a low internal capacity, which were obtained from the research laboratories of the General Electric Co., with the smaller oscillator it was possible to generate effective oscillations of a frequency around 200,000,000 cycles per second, and feebler ones of possibly 230,000,000 cycles.

As shown by the photograph, this tube has the filament and plate leads brought out at the lower end of the tube while the grid lead is brought out at the top. This reduces the capacity between leads within the tube which, in the ordinary type of mounting, may be several micromicrofarads.

Measurements of the internal capacity of this tube made at 1,000 cycles on the Cruft Laboratory capacity bridge showed this to be between 3 and 4 micromicrofarads, less than one-half that of a standard UV 202, 5-watt tube.

While the tubes, when received, were provided with bases, these were removed, by heating, before use so as to reduce the tube capacity to a minimum.

It was found that the generation of these high frequencies was very hard on the tubes, it being necessary, in order to secure adequate output, to increase the filament and plate currents considerably beyond the normal standard. This resulted in burn-outs, cracking of seals, and, in the case of the UX 210 tube, of depletion of electron emission beyond the possibility of reactivation.

For frequencies of 60,000,000 cycles per second and less it was no longer found necessary to use the type of oscillator just described, which, though reliable and stable in operation, nevertheless, because of limited range was not as well suited to the exploration of the lower frequencies, as the ever useful and efficient Hartley circuit. Consequently, for these lower frequencies, the latter circuit with parallel plate feed, through a choke coil, was employed as shown in Figure 2 and the accompanying photograph.

For the inductance, single turn loops of No. 14 to No. 4 wire were used according to size and the need for rigidity. These loops, as shown in the photograph, were supported on the tuning condenser (a low-priced 5-plate affair with bakelite end plates which was found to function as satisfactorily as one of the most expensive "low loss" construction).

For frequencies below 12,000,000 cycles, however, a high-grade 17-plate condenser was used. The plate-blocking condenser, a Dubilier micadon, had the value of .00025 mfds. The filament return was

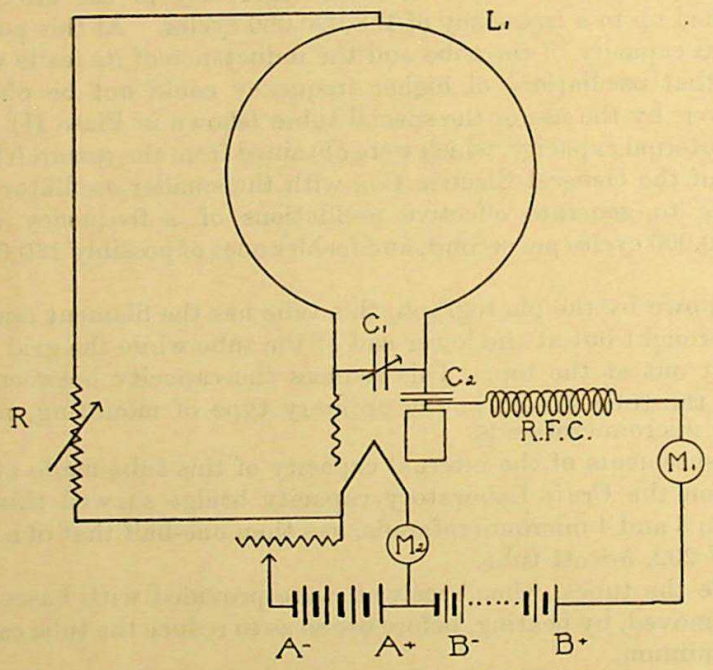



FIG. 2.—Circuit diagram of oscillator No. 3 (Hartley circuit)
$L_1$, Plate and grid inductance
$C_1$, Tuning condenser (5-plate and 17-plate)
$C_2$, Blocking condenser
$R_1$, Variable resistance (10,000–200,000 ohms)
R. F. C, Radio-frequency choke-coil
$M_1$, Plate millammeter
$M_2$, Filament ammeter

taken off the mid-point of the tuning inductance, the connection to the negative filament being made, as in the case of the other oscillators, through a variable Bradley resistance, the usual resistance values used being from 10,000 to 15,000 ohms.

Choke coils of several sizes were inserted in the plate feed, larger choke coils being used for the lower frequencies. As in the case of the oscillators previously described, these consisted of a self-supporting spiral of No. 18 or No. 20 D. C. C. wire, the number of turns varying

from 23 to 65 or 70 and the diameter from 2.5 to 4 centimeters, the turns being spaced about the diameter of the wire.

With this type of oscillator, simply by varying the diameter of the single turn used as the inductance, with the 5-plate condenser it was possible to go from 66,000,000 cycles per second (using a 6-centimeter loop) to 10,000,000 cycles per second (using a turn of No. 4 copper wire 76 centimeters in diameter). With a single turn loop 32 centimeters in diameter tuned by a .00035 mfd. condenser, frequencies as low as 7,500,000 cycles could be readily generated.

In all the oscillators the filament temperature was controlled by a 2-ohm rheostat. A Weston ammeter in the filament circuit and a Weston 0–300 milliammeter in the plate circuit indicated the filament and plate currents, respectively. The latter instrument was placed in the negative plate-battery lead and was protected by the insertion of a short strip of ¼-ampere fuse wire.

It was generally found that, for adequate output, the necessary plate current was considerably greater at the higher than at the lower frequencies. At the highest frequencies, during some of the runs, plate current readings of from 100–120 milliamperes were not unusual, but at the lower frequencies from 50 to 80 milliamperes was the usual value.

*Frequency determination.*—For the purpose of ascertaining the frequency at which the oscillator was operating, use was made of a Lecher parallel wire system. This consisted of two No. 12 parallel copper wires 7.5 centimeters apart and 11 meters long, stretched from standards 29 centimeters above the level of the workbench. Turnbuckles at one end of the wire system served to tighten the wires.

The slider was a rectangular piece of 22-gauge brass plate 12.5 by 8 centimeters, provided with two parallel slots 7 centimeters long and 7.5 centimeters apart to enable it to engage the wires. Supporting sliders of bakelite, grooved to fit the wire and attached front and rear steadied the slider plate, enabling it to travel smoothly. A waxed string passing over pulleys attached to the standards allowed the slider to be moved to any position from the operator's location. A plumb bob suspended by a waxed thread from the slider indicated its position with respect to a wave-length scale laid out on the workbench beneath. Resonance of the wire system with the oscillator frequency was indicated by a Weston thermogalvanometer connected across the oscillator end of the wires.

In a system of this character, as is well known, standing waves are formed on the parallel wire system in a series one-half wave in length between nodes. If the slider is placed at one of these nodes the wave will travel along the wires to the slider and be reflected back, the total distance traveled being equal to the distance between wave crests, and therefore corresponding to the wave length. When the

slider is located in this fashion at a node the meter will show the maximum deflection.

The system is readily calibrated by setting the oscillator at some frequency sufficiently high to permit the development of several successive nodes on the wire system, moving the slider to each of these points in succession and measuring the interval between them; and averaging the measurements which will be found to differ from each other by less than a centimeter. In this way orientation points on the wave-length scale are readily located from which the wave-length scale may be laid out, the wave-length measured, and hence the frequency determined.

Although, owing to the capacity between the wires and also to the surface of the bench, a slight error is introduced, so that the apparent frequency is slightly higher than the actual, still this method of measuring the wave length, and consequently the frequency, is remarkedly accurate, the error probably being one-half of 1 per cent or less.

Since available space permitted a wire system only 11 meters long, wave lengths only up to approximately 21 meters, or frequencies somewhat less than 15,000,000 cycles, could be directly measured. For lower frequencies a wave meter was employed. This consisted of a loop 32 centimeters in diameter made of ⅛-inch brass rod and a high grade .00035 mfd. condenser in series therewith, resonance being indicated either by the lighting of a low-resistance flash lamp bulb in series with the loop and condenser, or by observing the deflection in the plate-milliammeter needle of the oscillator at the resonance point. This latter method was preferred because of the sharpness of the reaction.

This wave meter was calibrated at the Cruft High Tension Laboratory by comparison with the Cruft Laboratory precision wavemeter for this range of frequencies which, in turn, had been calibrated against a quartz-crystal controlled oscillator.[3]

*Utilization of oscillator output.*—In studying the effects of the oscillator output at various frequencies upon laboratory animals it would obviously be inexpedient to make use of any conductive arrangement, as the constants of the oscillating system would thereby be seriously disturbed. In these studies, therefore, the effects of of these high frequency currents upon animals were investigated by the use of a tuned circuit which was inductively coupled to the oscillator.

As shown in the circuit diagram (fig. 3) and photograph (Pl. III), this tuned circuit consisted of a single-turn wire loop, having a thermocouple (to measure the current) inserted at its mid-point and a capac-

[3] See: Piezoelectric Crystal Resonators and Crystal Oscillators Applied to the Precision Calibration of Wave-meters. By George W. Pierce. Proceedings of the American Academy of Arts and Sciences, vol 59, No. 4.

ity consisting of a pair of rectangular brass plates 7.4 by 4.3 centimeters, 2 centimeters apart. The separation of the plates was rigidly fixed by means of four ¼-inch hard-rubber posts each 2 centimeters long at each corner of the plates. Since it was determined to study the action of the electrostatic field between the condenser plates, to avoid any conductive transfer of energy the inner surface of each condenser plate was covered with a celluloid sheet 0.004 inch in thickness. The subject for experimentation (a mouse) was placed in a small celluloid box with perforated sides (see Pl. III) and inserted between the condenser plates where it fitted snugly.

The dimensions of the condenser given above were not the result of any calculation, but were determined by the size of the celluloid box which was designed to hold a 20–22 gram mouse comfortably without, at the same time, permitting it to turn and twist too freely. The box consisted of two pieces of stout celluloid for the top and bottom, held apart by ¼-inch hard-rubber posts to which they were secured by short screws in holes tapped at each end of the posts. The sides of

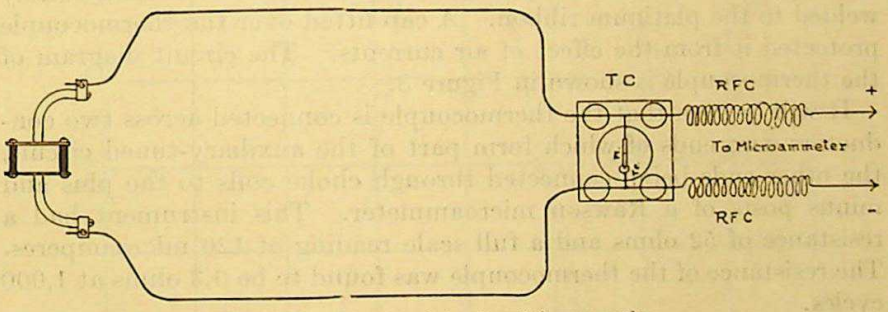



FIG. 3.—Auxiliary-tuned circuit and thermocouple

the box were covered in with strips of stout celluloid perforated with numerous ¼-inch holes for ventilation, glued to the hard-rubber posts by means of cellulose varnish.

While mice of from 19–22 grams in weight fitted snugly in the box, so that they could indulge in but moderate twisting and turning about, still, confinement in the box was apparently not uncomfortable per se, as mice frequently went to sleep when undisturbed. Confinement in the box of several hours' duration was without effect upon mice.

The capacity of the condenser without mouse or mouse holder was found to be 4.1 micromicrofarads. Putting the empty mouse holder in place increased the capacity to 8.1 micromicrofarads. With a 20-gram mouse in the holder the capacity increased to 16.1 micromicrofarads. These measurements were made at 1,000 cycles on the Cruft Laboratory capacity bridge. The capacity of the condenser with mouse holder and mouse was, therefore, about four times greater than the capacity with air alone as the dielectric.

*Current measurement.*—The amount of oscillating current induced in the auxiliary-tuned circuit was measured by means of a platinum-tellurium thermocouple which was constructed for the writer by Mr. F. H. Drake, of Cruft Laboratory. This consisted of a bit of tellurium supported upon a piece of 22-gauge nickel wire to which it was fused. This in turn was soldered to a short piece of No. 18 copper wire. A piece of 7-mil. platinum wire was rolled to a ribbon approximately 1 mil. in thickness. A piece of this about 1 centimeter long was soldered at one end to a short piece of 18-gauge copper wire, while the other end was made somewhat pointed by means of shears. The pieces of copper wire to which, respectively, the platinum ribbon and the tellurium were attached were mounted vertically, through holes in which they were a tight fit, on a stout piece of bakelite at such distance apart that the pointed end of the platinum ribbon fell naturally about on the center of the tellurium fragment. Upon passing direct current regulated by a variable resistance from a 6-volt storage battery, the platinum ribbon was heated to redness. The tellurium fused at the point of contact and thus became solidly welded to the platinum ribbon. A cap fitted over the thermocouple protected it from the effect of air currents. The circuit diagram of the thermocouple is shown in Figure 3.

It will be seen that the thermocouple is connected across two conductors, two ends of which form part of the auxiliary-tuned circuit, the other ends being connected through choke coils to the plus and minus posts of a Rawson microammeter. This instrument had a resistance of 52 ohms and a full scale reading of 120 microamperes. The resistance of the thermocouple was found to be 0.3 ohms at 1,000 cycles.

The thermocouple was calibrated on 60-cycle A. C. by noting the scale reading of the microammeter for various current values as determined by the voltage drop across standard resistances measured by a Rawson vacuum thermocouple voltmeter. The full scale reading of 120 on the microammeter corresponded to 0.61 amperes. At 5 on the scale the current was 0.139 amperes.

The calibration of this thermocouple was checked at frequent intervals throughout the study and remained unchanged.

*Tuning the auxiliary circuit.*—Since the output of the oscillator was applied to the experimental animals, by means of the current induced in the auxiliary circuit placed in inductive relation to the oscillator, the first step in any experiment was, of course, to tune the coupled circuit to the oscillator frequency so that the current in this circuit should be a maximum. To do this, a mouse immediately after death by gas was placed in the celluloid box and inserted between the condenser plates. A loop was then formed by joining with two pieces of stiff wire the high frequency terminals of the thermocouple with the corresponding condenser terminals. As a first ap-

proximation the length of wire was arbitrarily chosen at a value which experience showed to be about the length desired. Then by starting the oscillator and varying its tuning condenser until maximum current was flowing in the coupled circuit, upon determining the frequency an idea could readily be had of how closely the auxiliary circuit was tuned to the frequency it was desired to study. With

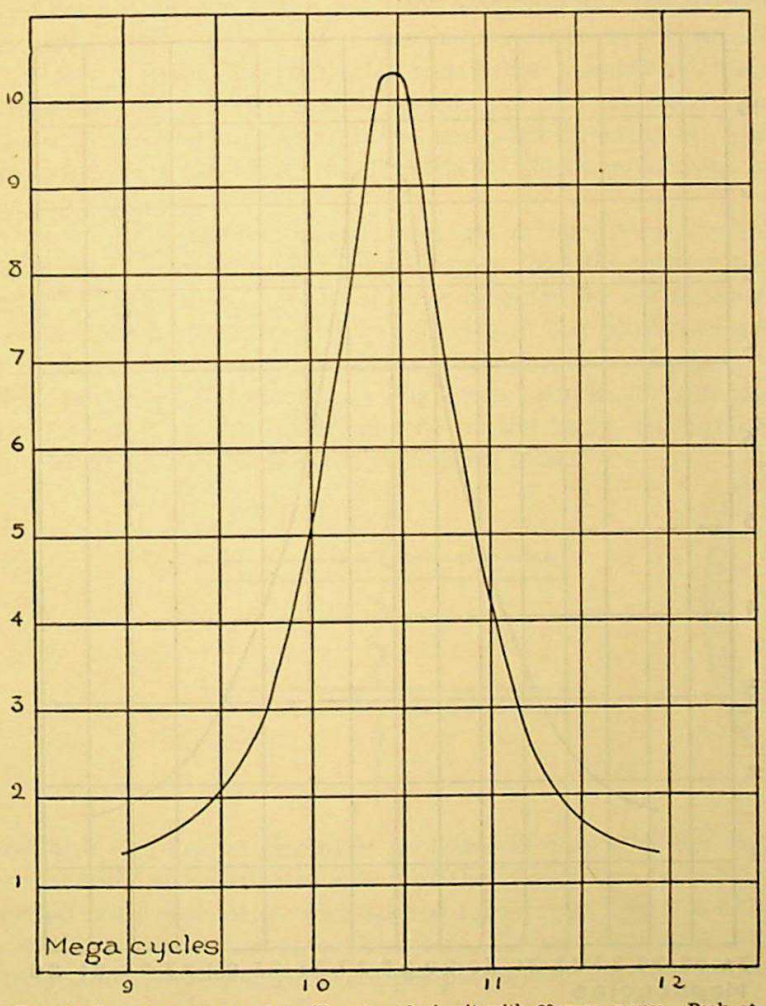



FIG. 4.—Resonance curve of auxiliary-tuned circuit with 20-gram mouse. Peak at 10.42 megacycles

this information it was easy to add or to subtract wire from the auxiliary circuit as required, fine adjustment being finally made at the condenser terminals by loosening the set screws which held the wire in place in holes in the arms supporting the condenser and adjusting the length of the inductance by pushing the wires in or pulling them out of the holes. The graphs (Figs. 4 and 5) of the resonance peak

of the tuned auxiliary circuit measured at 10,400,000 cycles, and at 28,400,000 cycles, give a good idea of the type of resonance obtained in this circuit.

It will be noted that the circuit tunes more sharply at the lower frequency. In this case the peak of the resonance curve is about 180,000 cycles broad, while, at the higher frequency, the breadth of the peak is about 1,200,000 cycles.

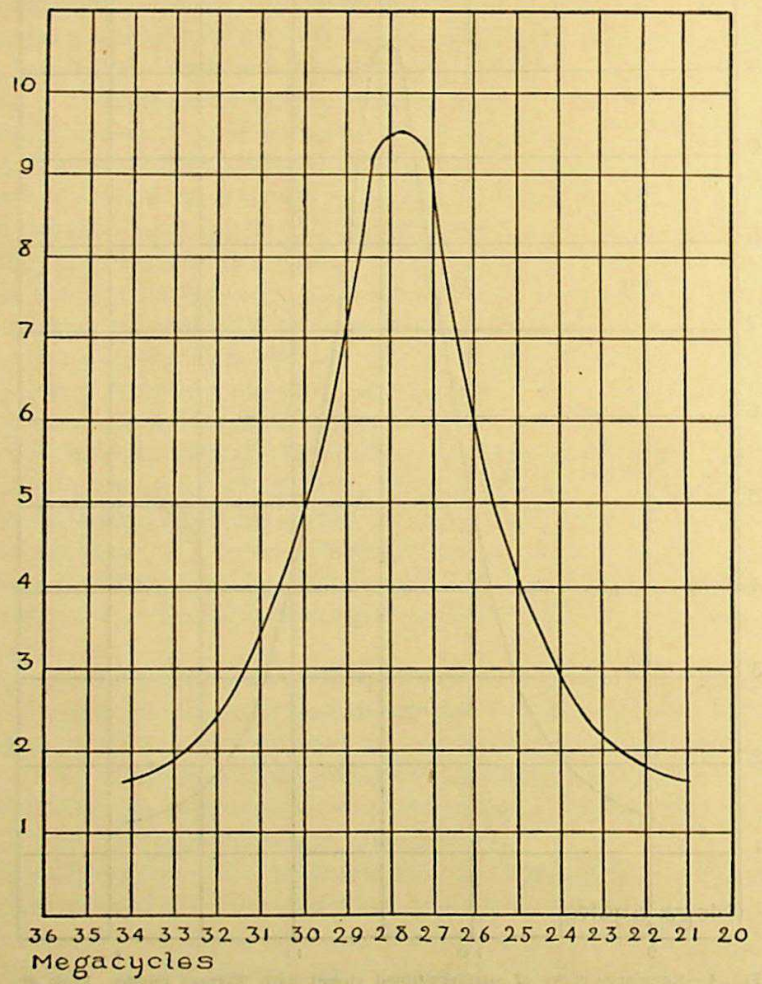


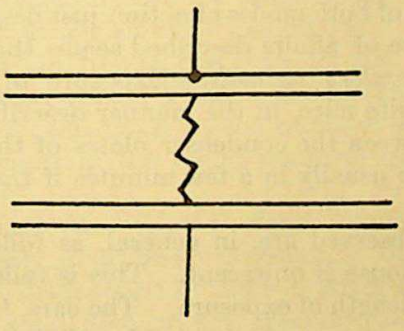

FIG. 5.—Resonance curve of auxiliary-tuned circuit with 20-gram mouse. Peak, 28.4 to 27.2 megacycles

We may, therefore, conclude, since the tuning of the auxiliary circuit is rather broad, that this circuit presents considerable resistance. Hence, only approximate accuracy is necessary in setting the auxiliary circuit to resonance as the current flowing through it, when tuned to somewhere near the oscillator frequency, is ample for experimental purposes.

### Effects of Exposure on Laboratory Animals

It will be noted in the auxiliary circuit just described that the experimental animal, insulated in a box of nonconducting material, is placed in the field between the plates of the condenser while the coupled circuit is excited by the oscillator at some particular frequency. Consequently, no free electrons from the external metallic parts of the circuit can enter, nor can they flow out from the body of the experimental animal. The mouse, however, is subjected to a displacement current, in which electrons in the molecules of the body cells will, according to their state of freedom, either pass from molecule to molecule, first in one and then the other direction or, if bound, are stressed in a direction the polarity of which alternates at the oscillator frequency.

The equivalent electric circuit presents at least two possibilities. The first and more probable possibility is that the system may be regarded as two condensers in series connected by a resistance, the first condenser being formed by one plate of the condenser and the body surface of the mouse, in close proximity to it, the intervening celluloid acting as a dielectric. The second condenser is formed, in similar fashion, by the lower surface of the body, the intervening tissues acting as the connecting resistance thus:



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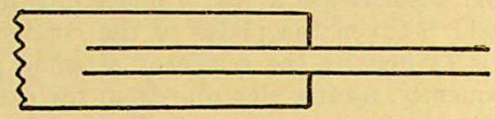
That this equivalent circuit is probable is shown by the fact that we can readily substitute in place of the mouse two metallic plates connected with each other and spaced far enough apart to fit snugly against the top and bottom of the box. It was determined experimentally that two rectangular copper plates each 2.5 by 2 centimeters and spaced 2 centimeters by a connecting copper strip furnished an electrical equivalent for a mouse. If the coupled circuit were tuned to the oscillator frequency with this arrangement in the box, it was found to be approximately in tune if a mouse were substituted. However, the coupled circuit with the substitute in place had naturally a much lower resistance than with a mouse, so that the current registered for a given filament temperature was considerably higher.

Another possibility is that the mouse's body acts in the circuit as a dielectric of poor quality. In this case the electric equivalent would be a condenser shunted by a resistance as shown below.



It has already been mentioned that the insertion of the mouse holder containing a 20-gram mouse between the condenser plates increased the capacity about four times. The effect of the presence of the mouse holder and mouse on the tuning of the circuit is well shown in the following way. When the auxiliary circuit, with the mouse in place, is tuned to the oscillator's frequency, if the mouse holder and mouse are then removed the needle of the microammeter, indicating the current in the tuned circuit, drops to zero. If the oscillator be tuned to resonance with the circuit in this condition, the frequency will be found at a point considerably higher.

In this case, as might be expected, with a perfect dielectric, as air, filling the space between the condenser plates, the resistance of the circuit is lower, so that the resonance peak is sharper and the current flowing greater for a given oscillator output.

While it may well be that the electrical behavior of the mouse in the circuit partakes of both modes of action just described, still, on the whole, the first state of affairs described seems the more likely

*Effects upon laboratory animals.*—Exposure of small laboratory animals, such as white mice, in the manner described, to the rapidly oscillating field between the condenser plates of the auxiliary tuned circuit, causes death usually in a few minutes if the current value be sufficiently great.

The symptoms observed are, in general, as follows: For a short, variable time the mouse is quiescent. This is followed by agitation increasing with the length of exposure. The ears, tail, and paws turn a bright pink which, in many instances, becomes livid or cyanotic as the exposure is prolonged. There is salivation, the nasal secretion is increased; the head and under parts of the body become wet and bedraggled; the paws are covered with beads of moisture. After a variable time convulsions accompanied by convulsive winking take place, dyspnea sets in, and finally respiration ceases. In males there is usually considerable swelling of the genitalia. The heart, however, continues to beat for a little while after respiration ceases.

In the great majority of instances the body of the mouse appears distinctly warm to the hand, and if the rectal temperature be taken immediately after death considerable elevation in the body temperature is found to have taken place, the temperature varying from 42.2° to 43.1° and even 44° C. However, this is not always the case, as death was repeatedly observed to occur in the usual time, and yet the elevation of the body temperature was only moderate,

in one instance the rectal temperature not exceeding 39.2° C., a temperature which is not infrequently observed in apparently normal mice. However, in the majority of instances the exposure has caused considerable elevation of the body temperature and we may infer that the primary fatal effect observed consists in raising the body temperature to a degree incompatible with life.

Since the rectal temperature of a normal mouse, according to the temperature of the environment, may be anything from less than 37° to about 39° C., the exposure has brought an increase of the body temperature of anywhere from 5° to 6° C.

In the case of mice, however, which had been killed by exposure to carbon monoxide gas, and then immediately exposed in the coupled circuit, the heating effect was far less pronounced. In dead mice it was found, using the same current and time of exposure necessary to kill living mice at that particular frequency, that the rise in the body temperature of the dead mouse was of a much lower order, amounting to but 0.7° to 1° C. In many instances there was no gain, and in others a loss was recorded.

This would suggest that the heating effect is different from the diathermic effect observed at the lower frequencies used for therapeutic purposes, as by the use of high-frequency current in diathermic apparatus it is easy to raise the temperature of dead tissues well above the point at which albumen coagulates.

However, at certain frequencies considerable heating effect was observed even in dead mice. Thus, at 6.6 meters, or a frequency of 45,000,000 cycles, 3 dead mice, as the result of exposure lasting 8.5 minutes, showed gains in the rectal temperature of 2.33° 3.6° and 4.4° C., respectively.

*Sequelæ of exposure to sublethal doses.*—Apart from the acute symptoms previously mentioned exposure to these high-frequency currents may cause destruction of tissue. After sublethal exposures, in many instances, small hemorrhagic areas may be observed along the course of blood vessels of the ears. In the course of 48 hours the ears become necrotic and drop off. The tail also often presents numerous ecchymotic areas. It may subsequently become affected with dry gangrene and drop off. In other instances areas of alopecia develop, particularly in the supra-orbital region or at the tip of the snout. In one instance a panophthalmitis developed with subsequent loss of vision.

*Effects of change in frequency.*—In preliminary observations it soon became evident that the effects of exposure to different frequencies was not the same, a current of constant value proving more lethal at some frequencies than at others. Furthermore, the change in lethal effect did not appear to bear any simple relation to change in frequency, as one would be led to expect, so it was determined to study the changes, if any, in the lethality of a constant current as the

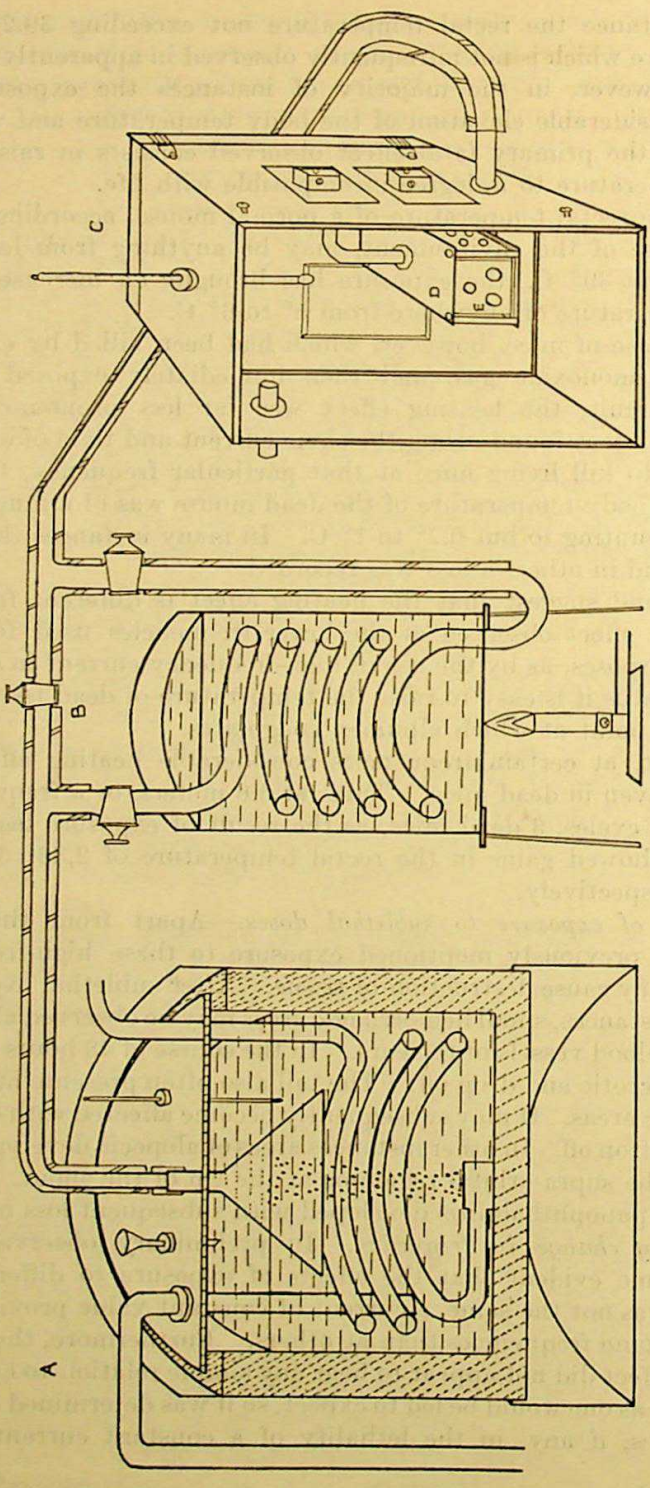



FIG. 6.—Constant temperature and humidity apparatus. A, Humidifier; B, Hot-water bath; C, Box containing condenser; D, Condenser; E, Mouse holder

frequency changed. Since part, at least, of the effect of the exposure was due to increase in the body temperature which, in turn, might be modified by changing external temperature conditions, it was evident that, to avoid serious error, the observations must all be made under substantially constant meteorological conditions.

The standard conditions of temperature and humidity at which to conduct the experiments were arbitrarily fixed at 24° C. and 40 to 42 per cent relative humidity, as these represented a fair average of the atmospheric conditions at which preliminary observations were made.

To secure these conditions, the apparatus depicted in Figure 6 was set up. As will be seen from the diagram, it consisted of the following parts:

The condenser, in the field of which the mouse was exposed, was mounted in a wooden box 22 by 10 by 9.5 centimeters outside dimensions. The front and back sides of the box, provided with celluloid windows for observation, were removable and were held in place by stout rubber bands. To secure a close fit, the inner side of each was fitted with a rubber gasket 1 centimeter wide which bore against the edges of the box.

Air taken from the laboratory compressed-air supply was first cooled and partly saturated by bubbling through water in a large wash bottle, which itself was cooled to approximately 10° C. by immersion in water of that temperature. The air issuing from the wash bottle was piped to a copper coil inside a large container packed in sawdust and filled with water which was kept at a constant temperature of 10° C. From the copper coil the air issued in a stream of fine bubbles, from a bubbler consisting of a small, weighted tin can, the open end of which was covered with 8 or 10 thicknesses of butter cloth. The air, cooled to 10° C., and thus practically fully saturated with moisture at that temperature, was piped through a jacketed copper pipe to the box in which the condenser was mounted, entering at the bottom through a glass tube in a perforated rubber stopper tightly fitted in a hole in the side of the box.

The ventilating current, rising through the box, issued through a similar glass tube at the top of the opposite side. A ventilation of about 8 to 9 liters per minute was maintained through the box. A centigrade thermometer inserted through a perforated rubber stopper in the top of the box indicated the interior temperature.

Since the amount of moisture which fully saturates air at 10° C. will leave it only 42.1 per cent saturated at 24° C., it is obvious that, to secure the standard atmospheric conditions determined upon, all that is necessary is to see that the temperature of the box is maintained at 24° C., or as close to that figure as is practicable.

In order to provide means of heating the air when necessary, a coil of copper pipe in a hot-water bath was provided in the vicinity of the box, through which air could be by-passed, before reaching the box, by means of two stopcocks, as shown in the figure. In this

manner, whenever, owing to external conditions, the temperature of the box tended to fall below 24° C., the incoming air could be led first through the copper coil in the hot-water bath and thus heated to the necessary extent. Since, when heated, no moisture would be lost, nor could it gain any, upon cooling to the temperature of the box, the relative humidity would comply with the conditions.

With the apparatus just described a large number of observations were made at a constant current and at frequencies varying from 135,000,000 to 8,330,000 cycles per second. The constant current employed caused a deflection of 30 divisions on the scale of the microammeter, corresponding to a current of 338 milliamperes flowing in the auxiliary tuned circuit.

This value of current was chosen because preliminary observations had shown that, at lethal frequencies, this current value always caused death in 10 minutes or less. In the great majority of instances ten mice weighing between 19 and 22 grams were used successively at each frequency and sometimes more were used.

The difference in frequency employed was in the neighborhood of 10 per cent. This accounts for the fact that many of the frequencies and wave lengths given in Table 1 are not integers. In that table are set forth the frequencies at which observations were made, the number of observations, the average time elapsing before death, the maximum time, the minimum time, and the usual time.

TABLE 1

| Frequency times $10^6$ | Wave length | Number of observations | Average length of survival | Minimum length of survival | Maximum length of survival | Usual length of survival |
|---|---|---|---|---|---|---|
| | *Meters* | | *Minutes* | *Minutes* | *Minutes* | *Minutes* |
| 135 | 2.22 | 8 | 26.4 | 16.5 | [1] | 21 -25 |
| 121.5 | 2.47 | 10 | 20.1 | 13.5 | 26.5 | 20 -22.5 |
| 110 | 2.73 | 10 | 15.9 | 11.5 | 20.0 | 17 |
| 99 | 3.03 | 11 | 15.6 | 9.25 | 23.0 | 14.5-16 |
| 90 | 3.34 | 12 | 10.9 | 8.0 | 17.5 | 9 -12.5 |
| 81 | 3.7 | 9 | 9.9 | 7.0 | 16.5 | 8 -10.5 |
| 73 | 4.11 | 10 | 9.5 | 6.5 | 15.5 | 9 - 9.5 |
| 66 | 4.54 | 10 | 7.7 | 6.0 | 9.0 | 7 - 8 |
| 60 | 5.0 | 9 | 8.0 | 5.5 | 9.5 | 7 - 9 |
| 55 | 5.44 | 10 | 9.25 | 5.0 | 12.0 | 9 -10 |
| 50 | 6.0 | 6 | 9.37 | 7.0 | 11.0 | 8.5-10 |
| 45 | 6.66 | 14 | 7.8 | 4.5 | 10.5 | 7 -8.5 |
| 42.8 | 7.0 | 5 | 8.1 | 6.0 | 11.5 | 7 - 8 |
| 40.1 | 7.25 | 10 | 7.6 | 6.0 | 9.5 | 7 |
| 35 | 8.51 | 16 | 9.1 | 6.5 | 14.5 | 7.5- 9.5 |
| 30 | 10.0 | 10 | 8.5 | 7.0 | 10.5 | 7.5- 8.5 |
| 27 | 11.11 | 10 | 6.65 | 5.0 | 8.0 | 6 - 7 |
| 24.3 | 12.3 | 10 | 10.52 | 8.5 | 14.0 | 9.5-10.25 |
| 22.22 | 13.5 | 13 | 7.8 | 5.0 | 12.0 | 6.5- 7.5 |
| 20 | 15.0 | 12 | 8.27 | 6.0 | 11.5 | 7 - 8.5 |
| 18 | 16.6 | 15 | 6.96 | 4.5 | 9.5 | 5.5- 6.5 |
| 16.2 | 18.5 | 11 | 7.1 | 5.5 | 11.5 | 6 - 7.5 |
| 14.6 | 20.55 | 9 | 11.3 | 7.75 | 15.0 | 10.5-12 |
| 13.7 | 21.9 | 10 | 10.6 | 7.5 | 16.5 | 10 -12 |
| 12.33 | 24.4 | 10 | 14.25 | 9.0 | 19.5 | 12 -14.5 |
| 11.1 | 27.0 | 11 | 14.5 | 8.0 | 19.5 | 12 -13.5 |
| 9.93 | 30.2 | 10 | 9.65 | 6.5 | 14.0 | 8 - 9 |
| 9.2 | 32.5 | 9 | 11.5 | 7.5 | 17.0 | 10 -11.5 |
| 9.0 | 33.3 | 10 | 23.5 | 15.5 | [2] 35.0 | 22 -30 |
| 8.5 | 35.3 | 11 | 17.2 | 11.0 | [3] 30.0 | 16 -18 |
| 8.33 | 36.0 | 11 | 17.7 | 11.5 | 32.0 | 16 -19 |

[1] 1 mouse survived 43 minutes unaffected.
[2] 3 mice survived 35 minutes unaffected.
[3] 1 mouse survived 30 minutes unaffected.

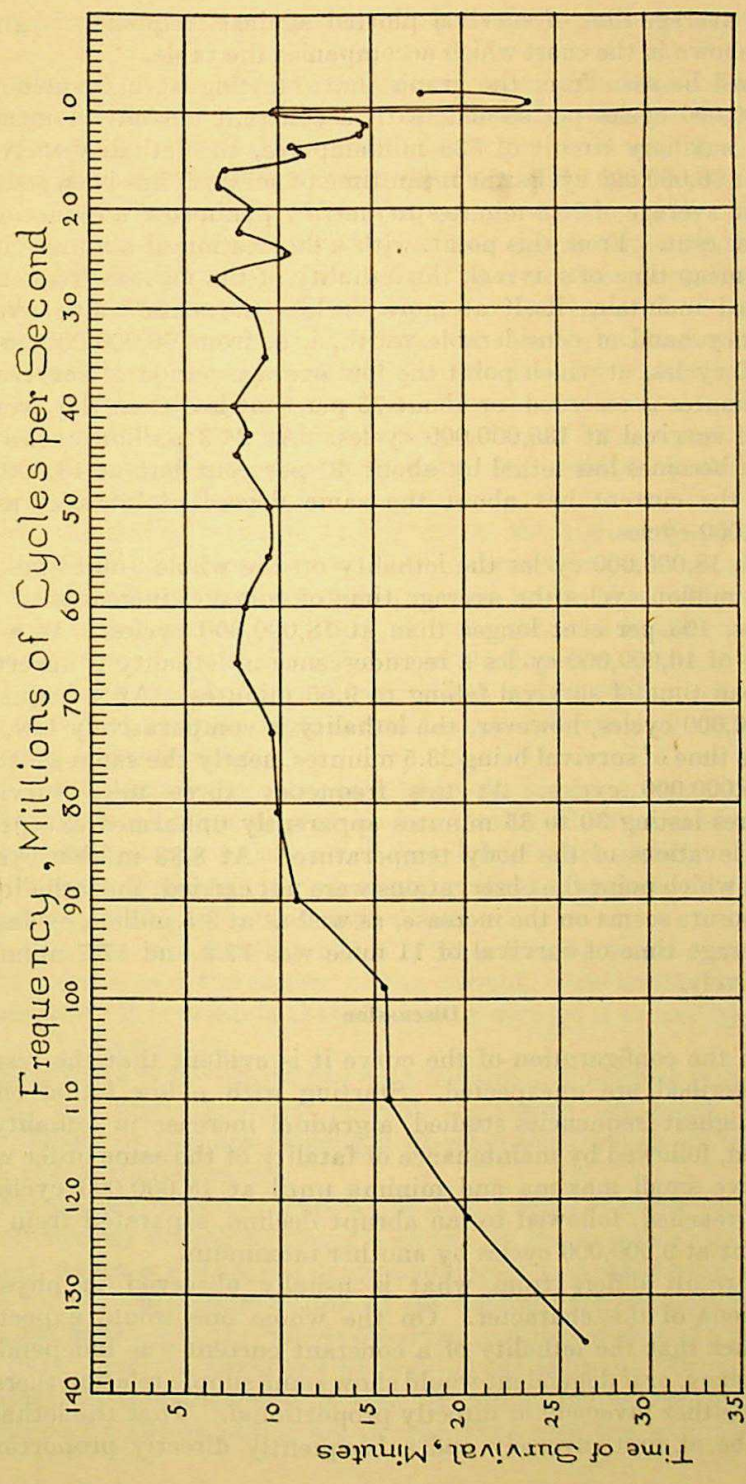



Chart showing the average time of survival of mice subjected to currents of various frequencies

The average time of survival plotted against frequency is graphically shown in the chart which accompanies the table.

It will be seen from the graph that, starting at a frequency of 135,000,000 cycles per second, with a constant current maintained in the auxiliary circuit of 338 milliamperes, the lethality increases until at 66,000,000 cycles the mean time of survival has been reduced from an average of 26.8 minutes to one of 7.7 minutes, a reduction of 71.3 per cent. From this point, with a fluctuation of a minute or so in the mean time of survival, the lethality of the various frequencies observed maintains itself at more or less the same value over a frequency band of considerable width, i. e. from 66,000,000 to 27,000,000 cycles, at which point the low average period of survival of 6.65 minutes is recorded, or about 75 per cent less than the average time of survival at 135,000,000 cycles. At 24.3 million cycles the current becomes less lethal by about 40 per cent but at 18,000,000 cycles the current has about the same degree of lethality as at 27,000,000 cycles.

From 18,000,000 cycles the lethality on the whole diminishes, till at 11.1 million cycles the average time of survival increases to 14.5 minutes, 105 per cent longer than at 18,000,000 cycles. At a frequency of 10,000,000 cycles a recrudescence in lethality is observed, the mean time of survival falling to 9.65 minutes. At a frequency of 9,000,000 cycles, however, the lethality is comparatively low, the average time of survival being 23.5 minutes, nearly the same as it was at 135,000,000 cycles. At this frequency three mice survived exposures lasting 30 to 35 minutes apparently unharmed except for slight elevations of the body temperature. At 8.33 million cycles, beyond which point the observations were not carried, the lethality of the exposure seems on the increase, as well as at 8.5 million cycles, as the average time of survival of 11 mice was 17.2 and 17.7 minutes, respectively.

### Discussion

From the configuration of the curve it is evident that the results just described are unexpected. Starting with a low lethal effect at the highest frequencies studied, a gradual increase in lethality is observed, followed by maintenance of fatality of the same order with successive small maxima and minima until at 18,000,000 cycles a peak is reached, followed by an abrupt decline, separated from the low point at 9,000,000 cycles by another maximum.

This result differs from what is usually observed in physical phenomena of this character. On the whole one would expect to find either that the lethality of a constant current was independent of frequency, or if dependent would show some simple relation thereto e. g., be either inversely or directly proportional. That the lethality should be at first inversely and subsequently directly proportional

to frequency is puzzling, and certainly not susceptible of any simple explanation.

At first one is tempted to assume that the results of the observation are apparent only. For instance, it might be urged that the apparent low lethality of the higher frequencies might be due to the "skin" effect of these frequencies upon the thermocouple.

As is well known, the high frequency resistance of conductors increases with the frequency, because, as this becomes greater, the current is confined to a surface pellicle of ever-diminishing thickness.

This so-called "skin effect" would occasion an increase with frequency in the apparent resistance of the thermocouple. Hence there would be a greater heating effect at the very high frequencies, and, as a result, a higher e. m. f. between the hot and cold junctions of the thermocouple, which would be reflected by a higher reading on the microammeter scale than would be justified by the actual oscillatory current flowing in the circuit.

That there may be some such effect at the highest frequencies is not denied; but how explain on these grounds the pronounced recession in lethality at the lower frequencies, where the "skin effect" is admittedly much less. Thus, we note that the lethality at 18.1 million cycles is about the same as at 24.3 million cycles, but very much greater (nearly 240 per cent) than at 9,000,000 cycles. Yet the skin effect, if important, should be more noticeable at 18,000,000 than at 9,000,000 cycles.

In view of the circumstance that, generally speaking, exposure to the oscillating current has very much less heating effect on dead than on living tissues, it may be suggested that, here, we are dealing with some action other than the direct heating effect observed at ordinary frequencies with diathermic apparatus.

In this case the heating effect is proportional to the product of the resistance and the square of the current. Under the conditions of this study it is possible that the heat generated is caused by dielectric loss or hysteresis.

Again there is the possibility that the action is indirect rather than direct, the high-frequency current increasing the basal rate of metabolism, or perhaps causing heat retention through its influence upon thermogenic centers.

That the effects of exposure to the high-frequency current are capable of directly damaging tissue is shown by the sequelae already described, which are observed in mice subjected to a sublethal exposure.

As for the differential action of the different frequencies, which is the most striking of the effects observed, nothing except of a speculative nature can be advanced by way of explanation. For instance, it might be thought possible that at certain frequencies harmonics generated by the oscillator are in resonance with the natural period

of organic molecules, particularly of animal proteids. These are well known to possess a very high molecular weight except for certain colloidal aggregates, perhaps the highest known molecular weights. Consequently, the natural period of resonance would be correspondingly low.

Nevertheless, in spite of the great size of the body molecules, the natural period of these, though relatively low compared with the molecules of simpler structure, would be sufficiently high to correspond to a wave length of from 0.5 to 3 or 4 millimeters, and hence to a frequency of six times $10^{10}$ to seven times $10^{9}$. The generation of definite harmonics of such a high order on the part of the oscillator seems altogether unlikely.

I am, however, indebted to Prof. George W. Pierce for the suggestion that the differential effects due to frequency may be caused by a mode of electromechanical vibration of the tissue cells, and for the accompanying reference to literature on the subject. Mechanical oscillations in solid elastic spheres have been given thorough mathematical treatment by Lamb.[4] A number of modes of vibration are analyzed and certain constants corresponding therewith are given. Some of the values of these constants (here designated "$K$") as given by Lamb, are: $K=0.66$, 1.89, 2.93, 3.94, 4.96, 5.97, etc., the lowest value corresponding to the mode of vibration having the longest period. Since a solid elastic sphere is capable of vibrating in a number of different successive modes, each of which has a frequency greater than that preceding it, such a sphere is capable of responding to impressed oscillations of different frequencies.

The frequency, $F$, at which the sphere vibrates in a particular mode is given in simplest form by the equation—

$$F=K\frac{V}{D} \tag{1}$$

where $F$ = Frequency of the particular mode of vibration.
$K$ = The corresponding constant given by Lamb.
$V$ = Velocity of the propagation of sound in the material composing the sphere.
$D$ = Diameter of the sphere.

From this equation it follows directly that the diameter of a sphere vibrating in a particular mode at frequency, $F$, is given by the equation—

$$D=K\frac{V}{F} \tag{2}$$

In this case let us assume that the velocity of the propagation of sound through tissue cells is approximately that of its propagation through water, i. e., $1.45\times10^{5}$ centimeters per second. For the

[4] Lamb, H.: On the Vibrations of an Elastic Sphere. Proceedings of the London Mathematical Society Series, 1, 1882, vol. 13, p. 189.

value of $K$ let us take 0.66, which corresponds to the mode of vibration having the longest period and thus to the diameter of the smallest sphere capable of vibrating in some mode at that particular frequency. For $F$ let us assume a value $F=40\times10^6$, a frequency somewhere in the middle of the band of lethal frequencies observed. Substituting these values in equation (2) we obtain for $D$, diameter of the sphere, 0.0024 centimeters or 24 microns. This diameter, while great for body cells, is, nevertheless, encountered in a number of cells in the nervous system. The diameter of the smallest sphere capable of oscillating at the highest frequencies worked with would be in the neighborhood of 7 microns, while at the lowest lethal frequency (lowest frequency of high lethality $10\times10^6$), this diameter would be 96 microns. This is greater than the diameter of any body cells except, perhaps, some of the giant pyramidal cells of the nervous system. However, in this instance one might venture the speculation that second or third order harmonics of the oscillator might, at the lower frequencies, possess sufficient energy to induce some form of electromechanical resonance in the body cells, although the fundamental frequency is too low to resonate with any except the sufficiently large body cells just mentioned.

As to the way in which electrical oscillations could induce mechanical vibrations in body cells, speculations are again in order. One possibility, at least, is that cell membranes act as dielectrics at the boundaries of cells. This would cause the contiguous surfaces of cells to act as condensers resulting in stresses of alternating polarity at the impressed frequency. A reinforcement of the effect resulting in mechanical vibrations would reasonably be expected when the frequency of the applied stresses approaches the natural period for mechanical vibrations of the cell. It would not, however, be expected that this frequency is critical, as such a system must, of necessity, be highly damped. So, if responsive, the response would merely be greater for a range of frequencies in the neighborhood of the frequency of mechanical vibrations.

### Conclusions

On the basis of the data gathered in the foregoing experiments, the following conclusions are permitted:

1. When small laboratory animals are placed in a box of insulating material and subjected to the action of a high frequency oscillating current in the field of a condenser resonating a tuned circuit, severe symptoms are caused which may result in death if the exposure is prolonged. Part at least, of the symptoms is due to heat retention.

2. This effect is most marked in a certain band of frequencies extending from $F=66\times10^6$ cycles to $F=18.3\times10^6$ cycles, the effect diminishing in one direction from a band extending from $F=66\times10^6$ to $F=135\times10^6$ and in the other from $F=18.3\times10^6$ to $F=9\times10^6$.

3. There is, consequently, at constant current, under the conditions of the experiments, a differential action with respect to frequency, the lethality of a constant current being in one region of the spectrum inversely and in another portion directly proportional to frequency.

4. In the band of frequencies studied, successive maxima and minima with respect to lethality occur which are most pronounced as the lower frequencies are approached.

Finally it may be remarked that here we are dealing with a band in the spectrum of radiant energy which as yet has been little studied in its effects on living cells. Since frequency is the sole differentiating characteristic in the whole band of radiant energy it is perhaps to be expected to find that in electromagnetic waves, frequency is a determining factor in their mode of action upon living organisms. It is thought that this is a field which will well repay further study.